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Methods of Soil Moisture Determination Under Field Conditions

by

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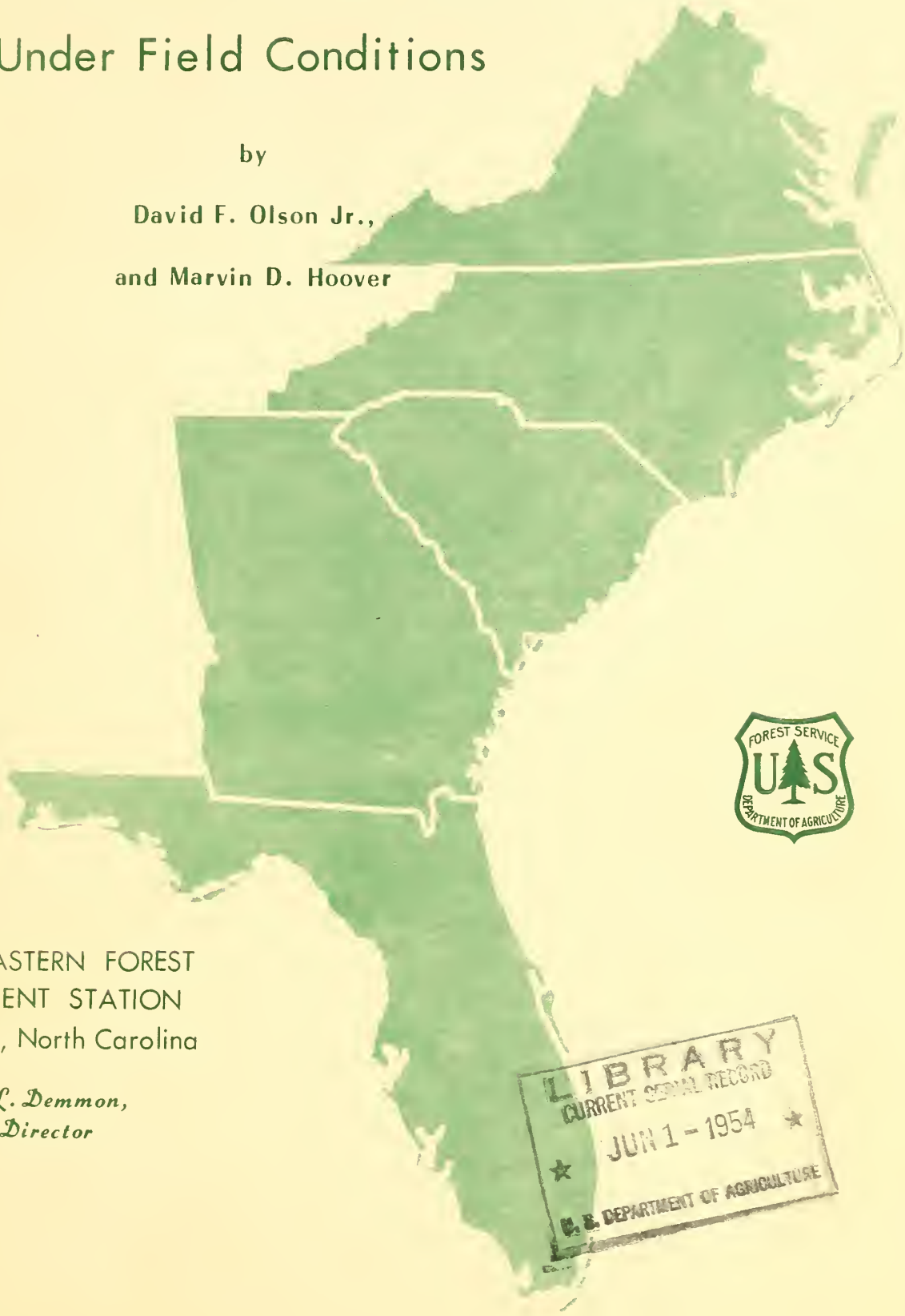

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METHODS OF SOIL MOISTURE DETERMINATION UNDER FIELD CONDITIONS

by

David F. Olson, Jr., and Marvin D. Hoover

CLASSIFICATION OF METHODS

The determination of soil moisture under field conditions is of vital importance to the agronomist, forester, hydrologist, and engineer. Those dealing in the plant sciences are primarily interested in the amount of water that is available to plants under various environmental conditions; the hydrologist and engineer are also concerned with soil moisture existing in the range above the field capacity and below the permanent wilting percentage. Continuous soil moisture measurement is necessary for full understanding of the nature of soil moisture movement, but limited studies of soil moisture are often needed as well. Any method of continuously determining soil moisture, in order to be universally acceptable, must be accurate in the complete range of soil moisture content from air-dryness to saturation. In practice no single method fulfills the above requirement, although the use of fabric electrical soil moisture units gives promise of doing so (8,9,10,11,33). Recently, researchers have been studying methods employing radio-active materials as well (6). At present most investigators rely on a combination of two or more methods if they are interested in studying the complete range of soil moisture.

Kelley, et al. (20) in 1946 admirably compared some of the important methods of measuring soil moisture under field conditions and gave an excellent outline classifying these methods as follows:

1. Methods based upon gravimetric measurements

    a. Determination of moisture in soil samples
    b. Determination of moisture in porous media in moisture equilibrium with the soil

2. Methods which depend upon the electrical properties of soil or porous media in moisture equilibrium with the soil

   a. Conductance or resistance methods
   b. Capacitance methods
   c. Dielectric methods

3. Methods based upon the thermal properties of the soil or porous media in moisture equilibrium with the soil

4. Methods which depend upon the measurement of the equilibrium tension on the water in a porous pot in contact with the soil

5. Methods dependent upon the resistance of the soil to penetration or deformation

In the gravimetric method of soil moisture determination samples are removed. Other methods can be used in which the soil remains in situ.

THE GRAVIMETRIC METHOD

Direct Sampling

The classical and only primary method of determining soil moisture quantitatively is to determine it gravimetrically on soil samples which are placed in airtight containers, weighed, dried to constant weight at 105° C., and reweighed. Water is reported as a percent of the oven-dry weight of soil (Pw). This is the standard method for determining soil moisture.

This gravimetric method is well adapted for certain soil moisture measurements, such as comparing moisture levels under various types of plant cover or treatments, ascertaining proper planting time, or determining optimum tillage conditions. In such cases where it is often neither necessary nor feasible to determine soil moisture continuously, a few soil samples will furnish data within 24 to 48 hours total elapsed time. In the limited-survey type of study the time factor is unimportant, and the gravimetric method is superior to all others in measuring soil moisture.

The initial requirement of soil moisture sampling is to obtain samples of soil which are representative of specific soil depths. Secondly, these samples must be placed in nearly airtight containers in order to minimize evaporation losses during handling. They must then be accurately

weighed, dried to constant weight at 105° C., and oven-dry weight obtained. It is often desirable also to obtain the weight of rock (2 mm. and larger diameter). Several soil sampling techniques have been devised. Those in use at the Calhoun Experimental Forest, near Union, S. C., are described below in detail.

In the majority of soil moisture investigations, the moisture content of the soil from the surface through a given soil depth must be determined. For this purpose soil tubes[1/] which are driven with an impact hammer are used in work at the Calhoun Experimental Forest. Soil tubes make it possible to extract samples without danger of contamination with other soil, and with little damage to the site (fig. 1). By marking the tube at specified intervals, soil cores of any length can be obtained. It will be found convenient to drive the tube only 6 inches before withdrawal. Each 6-inch soil sample is removed from the tube and placed in a marked can. The soil tube is then driven into the same hole for deeper samples (fig. 2). In practice, the depths of sampling should conform to soil horizons or layers so that a given sample does not include different types of soil material. The tube does not take a good sample from the surface few inches when the soil is loose, as in forest areas. It is convenient to sample this surface layer with a spoon or garden trowel.

Figure 1.--Driving soil tube. The hammer is in the man's right hand. A convenient box for carrying soil sampling cans is also shown. Keeping cans in the same order throughout the job to final oven-dry weight speeds up the work.

1/ The soil tubes used were manufactured by R. C. Jordon, 4616 Olivewood St., Riverside, California. They are made of 16-gage steel, have an outside diameter of 1-1/8 inch and an inside diameter of 1 inch, and are obtainable in lengths from 3 to 20 feet.

For most work a 4- to 6-foot tube is sufficient. Soil tube points are made of high-grade tempered steel, are removable, and have a taper hole approximately 3/4 inch at the tip end and 15/16 inch at the top end. Points are obtainable with taper designed for sampling in specific soil materials. Impact hammers are made of cast iron or steel and may be 14 or 16 pounds. The tubes are equipped with flanges at the top, which fit into slots in the hammer. This arrangement is for the purpose of pulling the tube out of the ground.

When sampling in tough, dry soils, it is often difficult to pull the tube by hand. Soil tube jacks with gripper jaws are useful for these situations, and increase the efficiency of the sampling operation (fig. 3).

It is good practice always to back-fill soil tube sampling holes with similar soil material and tamp them firmly. An iron pipe plugged in one end and of the same diameter as the tube makes an excellent tamping rod.

Figure 2.--Pulling soil tube. The driving hammer is slotted for flanges on the tube. Two men can usually pull a tube from depths of 4 feet.

Figure 3.--Use of jack to pull soil tube. One man unassisted can collect moisture samples with a jack to pull the tube. A jack is needed by a 2-man crew when sampling at depths below 4 to 6 feet when soils are dry.

The soil moisture sampling cans used are tinned iron boxes No. G about 3 inches in diameter and 2 inches deep, and hold approximately 230 cc.2/ The cans are made with a tight fitting lid. While samples are being taken in the field, they are kept in a covered back-pack box for easy transport to the laboratory (fig. 4).

A simple form for use in keeping field records, weighings, and computations is shown in figure 5. Fresh weights of the samples are obtained as soon as they are brought in from the field. A balance accurate to 0.1 gram is used. The weighing job can be speeded up considerably by use of a direct weighing scale. At this laboratory, samples are weighed first to the nearest 0.5 gram on a direct weighing scale to speed up the final weighing on a torsion balance.

2/ Supplied by Central Scientific Company, of Chicago, Ill.

Sample can lids are removed and the samples are then dried in an oven. Any oven in which temperature can be regulated between 100° to 110° C. can be used. The standard drying temperature is 105° C., but 100° may be found better for clay soils or soils of high organic content to avoid driving off water of hydration or volatile organic substances. On the Calhoun Experimental Forest a forced-draft oven is used and constant weight is reached in 12 to 16 hours of drying. In using ovens without forced draft, longer drying periods are necessary.

After oven-dry weight has been obtained, soil samples which have an estimated rock content of 2 percent by weight or greater are washed through a standard 2-mm. sieve. The oven-dry weight of the material retained on the sieve is the weight of rock, and is recorded in the proper place on the form. The removal of rock makes possible the direct comparison of quantities of soil moisture in soils with varying rock content, which would otherwise be impossible.

Tare weights of the sampling cans are redetermined twice annually and are recorded in tabular form to the nearest 0.1 gram for rapid use in all computations.

The computations to obtain soil moisture content in percent of oven-dry weight, percent by volume, and inches of water are then made as follows:

(1) Net oven-dry weight = oven-dry weight - (tare weight + weight of rock)

(2) Weight of water = fresh weight - oven-dry weight

(3) $Pw = \frac{\text{weight of water} \times 100}{\text{net oven-dry weight}}$

(4) Pv = Pw x bulk density of soil

(5) $\text{Inches of water} = \frac{Pv \times \text{inches of soil represented}}{100}$

Pw is moisture as percent of dry weight, and Pv is moisture as percent of volume. These expressions are discussed in more detail in the section of this paper headed "USE OF SOIL MOISTURE DATA."

Having discussed the techniques involved in soil moisture sampling, certain disadvantages of the gravimetric method for continuous soil moisture measurement are apparent. First, there is a definite physical limit imposed on the number of samples which can be collected in a single day. Time is always an important factor in continuous soil moisture studies, since they

deal with the most dynamic of all soil characteristics. For example, suppose one wished to measure soil moisture on a 40-acre watershed every day for one week following a storm of several inches, and suppose, further, that there were available only one two-man crew and equipment for the job. The number of sampling points established for daily remeasurement following this storm would be limited by the amount of work possible in a single day by these two men. Time must be allowed for weighing samples and sieving rock. These limitations alone point up why a continuous measure of soil moisture in the field is desirable, and why so much research effort has been devoted to its development in the past 60 years.

A second serious disadvantage of the gravimetric method is that removal of soil samples for moisture determination destroys the plot being studied. A common procedure in using soil sampling for continuous determination is to collect samples from the various depths in a series of holes and to return at regular intervals to remeasure the same plot. Obviously the exact locations can never be remeasured, and this introduces appreciable error in the results due to natural soil variability.

Figure 4.--The essential sampling equipment is readily portable. The box for sample cans is carried on a pack board.

Pit No______________

Date________________

Party_______________

Depth of sample	Can no.	Fresh weight	Oven-dry weight	Weight of rocks	Tare weight	Net oven-dry weight	Weight of water	Pw	Vol. weight	Pv	Inches of water	Average inches water

Figure 5.--Form used for soil moisture sample records and calculations at the Calhoun Experimental Forest.

Careful back-filling and tamping of sampling holes with similar soil material reduces the chance for water to seep down the old holes but does not remedy the main cause for error.

A third disadvantage of the gravimetric method for continuous determination is caused by the time lapse of 24 to 48 hours necessary before results of sampling are available. This lapse originates from the drying and weighing time required, and in stony soils, from the time for sieving of rock.

Despite the disadvantages cited, the gravimetric method of soil moisture measurement is the only one capable of direct measure of soil water quantitatively. All of the methods devised to measure soil moisture continuously in situ indicate water in a qualitative manner only, until they are calibrated against the gravimetric method in the field, or field checked by soil sampling if some laboratory calibration scheme is used.

Porous Media in Contact with Soil

In 1920, Livingston and Koketsu (22) attempted to measure certain plant-soil water relationships by the weighing of porous media in direct contact with the soil. Their approach was from the dynamic side in attempting to measure what they called the water-supplying power of the soil, somewhat as the evaporating power of the air is measured by means of atmometers. The method involved the use of small, porous-porcelain cones all having approximately the same area of surface in contact with the soil. At the time of a determination, a weighed, dry cone is thrust into the soil and left for a suitable time period, after which it is removed, quickly brushed free from adhering soil, and reweighed. The amount of water absorbed from the soil by the cone is taken as an approximate measure of the water-supplying power of the soil. In a controlled laboratory experiment, plants were grown in various mixtures of sand, loam, and humus; and wilting was allowed to occur. At the critical stage of permanent wilting the water-supplying power of the soil about the roots was determined, and it was found that this value was from 0.04 to 0.11 gram for 2 hours exposure for the porcelain cones used. The variations of this value from culture to culture were not related to the kind of soil or to its water-holding power; sand, loam, and humus all gave similar values.

In 1942, Davis and Slater (13) described an instrument which utilizes the direct weighing principle for continuous soil moisture measurement. The instrument consists of a porous chamber installed in the soil, and containing a closely fitted tapered porous plug which can be removed through a tube with a hook for weighing. The inner portion of the plug contains washed sand properly sized to provide an upper pore size range

corresponding to that in the soil. Weighings are made to 0.01 gram; the range in weight of the plug from dryness to saturation is approximately 5 grams.

A similar apparatus was developed by Richards and Weaver (28) and consists of a tube inserted in the soil serving as a mounting for the system. A second tube of smaller bore and with a rubber stopper on the end is inserted into the large tube to form a chamber at desired depth. A sorption-block 3/4 inch in diameter and 1/4 inch thick attached to a copper wire is suspended in this chamber and the top is closed off. Readings are made by weighing the suspended block. Installations of these units in 4-gallon crocks of soil at 4 levels of moisture content, sealed with paraffin and allowed to come to equilibrium for several weeks, reveal the following results:

(1) Blocks saturated with water come to constant weight in wet soil in less than a day.

(2) Dry blocks come to constant weight in wet soil in less than 3 days.

(3) Wet blocks come to constant weight in dry soil in less than 5 days.

(4) Blocks transferred between adjoining moisture levels either wetter or drier generally reach equilibrium within 2 days.

(5) A hysteresis effect was recognized; i.e., the equilibrium weight of a given block in a given soil depended on whether the block initially was wet or dry.

Lag in response of the gravimetric blocks to changes of soil moisture have limited their use, and much more research effort has been devoted to devising methods of soil moisture determination which make use of electrical and thermal properties of soil.

ELECTRICAL METHODS

The earliest work in this country to devise continuous methods of soil moisture determination date back to the 1890's with the work of the old Division of Soils. Whitney, Gardner, and Briggs (34) published in 1897 the results of about eight years of research with an electrical method of determining soil moisture based on the conductivity of soil. Using a Wheatstone bridge arrangement and soil electrodes consisting of carbon plates mounted on a wooden block, and also mounting with these electrodes

a temperature cell consisting of a known salt solution confined in a glass tube, they were able to follow soil moisture trends. However, these electrodes were never satisfactorily calibrated in the field. The authors established the fact that three principle factors influence the electrical conductivity or resistance of soils: temperature, moisture, and the soluble salt content. To determine any one of these, the other two must be known at time of observation. Consequently, other bulletins dealt with determination of temperature and salt content by electrical means. A second bulletin by Gardner (17) in 1898 was essentially a continuation of previous work. Certain refinements in the apparatus were described, however, such as the use of lead covered 3-conductor cable which allowed electrodes to be joined through underground connections with the measuring box. The box was mounted on a stand, covered, and left in the field in this work instead of being transported each time a reading was made. It was definitely established that decreasing soil moisture resulted in increasing soil resistance. One important objection to the 2-electrode method of measuring the electrical resistance of soil (though not recognized by these early workers) is that this method measures the sum of soil resistance and contact resistance between the electrode and the soil. Contact resistance is very erratic and unreproducible. The second objection arises from the fact that small changes in the salt content of the soil solution affect the resistance or conductivity more than does the amount of water present, and electrical methods of determining salt content were never perfected to correct for these changes.

Following this original work with the electrical method by the Division of Soils, a considerable period of time elapsed before new developments appeared. McCorkle (23) in 1931, working at the Texas Agricultural Experiment Station, used four electrodes made from carbon rods inserted in glass tubing to study soil moisture by the electrical resistance method. An A.C. bridge was used to measure resistance between individual electrodes, and an equation was then applied to derive soil resistance independent of contact resistance. It was possible to determine relative moisture contents with this method. McCorkle did not study the effect of salt concentrations on the instrument.

Edlefsen and Anderson (14) in 1941 published results of work with an apparatus quite similar to that of McCorkle. They used square iron rods for electrodes, but otherwise installed them and operated them as McCorkle had. They did, however, calibrate their instrument more carefully against gravimetric samples, and results showed similar resistances for the same moisture content during two separate cycles of drying following irrigation.

Working at the Michigan Agricultural Experiment Station, Bouyoucos and Mick (7) published in 1940 on an electrical method of measuring soil moisture which embodied a new principle. Instead of placing soil electrodes

in direct contact with the soil, they first imbedded them in a block of plaster-of-Paris. The area immediately around the electrodes was thus controlled so as to minimize the effects of texture, compaction, and salt concentration. When these porous blocks are embedded in the soil, the moisture content of the absorbent material varies with that of the soil. Its electrical resistance varies inversely as its moisture content; and hence, block resistance is an index of soil moisture. An adaptation of the Wheatstone bridge was used to measure resistances. Calibration of the units in small pans of soil in the laboratory produced satisfactory relationships in the range of soil moisture from the permanent wilting percentage to the field capacity, and limited tests indicated that these calibrations are applicable in the field as well. The effect of salt concentration of the soil solution on the block resistance was found to be small, and may possibly be attributed to the buffer capacity of the $CaSO_4$. Buffering has been defined as resistance to a change in salt concentrations. The authors conclude, however, that for accurate soil moisture determinations the block resistance should be corrected for temperature. One of the main disadvantages attendant upon the use of Bouyoucos blocks in humid regions is the fact that the blocks dissolve in the soil solution under field conditions after one or two growing seasons of use.

Anderson and Edlefsen (3), in a laboratory study with 2 and 4-electrode plaster-of-Paris blocks, placed blocks of each type in buckets of soil of different moisture contents which were sealed off with paraffin. This procedure was used to determine lag in response of the blocks where no plants were present. A similar procedure was used to determine lag in the presence of actively transpiring plants. Sunflowers were planted in the buckets of soil, and the whole was irrigated. Lead-foil sheets on the surface reduced evaporation. The results show that the blocks can be calibrated at all moisture contents by placing them in a soil surrounded by the roots of actively transpiring plants and then observing the relation between soil moisture content and block resistance. However, the blocks cannot be satisfactorily calibrated in the absence of such roots at the lower ranges of soil moisture content, because of the lag in response shown by the blocks to the value of the soil moisture content of the soil in which no plants are growing. The behavior of both the 2 and 4-electrode plaster-of-Paris blocks is remarkably reproducible. Under like soil moisture contents in the soils tested, the blocks always possess a like resistance at all soil moisture contents extending from the permanent wilting percentage to almost three times the moisture equivalent. As a soil moisture content indicator, the 2-electrode is better than the 4-electrode block because of simplicity in manufacture and in measurement of resistance. It has been shown in this study, as well, that the 2-electrode resistance of a plaster-of-Paris block is not very sensitive to variations in the separation of the two electrodes in the midplane of the block.

In 1946, Colman (10) published concerning a newly designed electric soil moisture meter which was developed on the San Dimas Experimental Forest of the U. S. Forest Service. The meter comprises two parts: the soil unit, which is buried in the soil and changes its electrical properties in response to soil moisture changes, and the meter unit, with which these electrical properties are measured. The soil unit is small, rigid, and resistant to corrosion and deterioration. The moisture absorbing dielectric through which the measurement is made is thin enough and completely enough exposed to the soil to eliminate any significant time lag in moisture indication. The measuring unit is rugged, portable, direct-reading, and self-contained for field use. The soil unit embodies the same principle as that employed in the plaster-of-Paris block; that is, the electrodes are shielded from direct contact with the soil by a porous dielectric. Specifically, the soil unit consists of two monel screens acting as electrodes and wrapped by three thicknesses of fiberglas fabric, which acts as the porous dielectric. This electrode sandwich and the electric thermistor are then wired, and the whole is pressed between two monel sheets. After complete assembly, the soil unit is only 1.5 by 1.0 by 0.12 inches.

The meter unit is an alternating current ohmmeter, and is entirely self-contained. A battery-operated vacuum-tube oscillator generates low frequency alternating current which passes between the electrodes. The measuring current is rectified and its magnitude indicated on the dial of a microammeter. Operation consists merely in zeroing the meter, pressing the switch, and reading the microammeter dial. Dial readings are directly related to resistance. The temperature measurement is made with a separate circuit in the same meter designed specifically to measure small differences in resistance over a limited range.

Colman and Hendrix (11), working with a somewhat improved model of the Colman soil moisture meter described above, conducted studies with the units to establish certain relationships between unit resistance and soil moisture equilibrium constants as well as other facts about the behavior of the newly designed soil units. For most soils the following resistance relationships exist: saturation, 150 ohms; field capacity, 600 to 1,000 ohms; and wilting percentage, 30,000 to 100,000 ohms. Detection of freezing and thawing of soil water is possible because the resistance of a water-saturated soil unit increases markedly when the water in the unit has been frozen. Other investigations with the instrument in this study showed the following:

(1) By indirect means using a pressure membrane apparatus, a calibration curve can be constructed so that moisture tensions can be related to resistance measurements.

(2) A random lot of manufactured soil units are closely uniform.

(3) Distilled water should be used in laboratory calibration.

The three main advantages of the Colman unit over the Bouyoucos block are: soil moisture can be measured from saturation to nearly air-dry; the unit does not dissolve or disintegrate in the soil solution; and there is less lag in response to moisture changes. Hence, an installation of Colman units may be operative up to 10 years or longer. The writers have found, however, that in laboratory calibrations of Colman units at the Calhoun Experimental Forest the units have proved to be much less sensitive to moisture changes in the upper half of the range between saturation and field capacity than Colman had intended.

In a study of the effects of salinity on soil moisture-electrical resistance relationships, Ewart and Baver (15) found that Bouyoucos plaster-of-Paris units are reliable in measuring moisture when salinity of the irrigation water used is up to and including 2,000 p.p.m., NaCl. Results of this study also indicate that Colman fiberglas units are very sensitive to the electrolytic effects of salts and that a concentration of 1,000 p.p.m., NaCl is sufficient to produce a significant lag in resistance value.

Bouyoucos and Mick (8) reported in 1948 on the results of 5 years of research with various types of fabric absorption units for continuous measurement of soil moisture. The purpose of this research was twofold; namely, to discover a means of measurement of soil moisture in the range from saturation to air-dryness, and to provide an electrode absorption unit that would function despite long periods of exposure in saturated environments. Twenty-five kinds of electrode absorption units were investigated. The fabrics employed were nylon and fiberglas, and in addition, rubber spong, asbestos, and bare electrodes were employed. Electrode metals tested included paladium, monel, copper, magnesium, stainless steel, pure nickel, and sterling. The fabrics were cemented to the metal plates and then pressed. The final fabric unit developed is very similar to the Colman unit previously described and consists of two perforated, extremely thin nickel plates, or two pieces of fine monel metal screen acting as electrodes, to which are silver-soldered wire leads. These electrodes are separated by wrappings of nylon or fiberglas fabric. The whole assemblage is then placed in a perforated nickel case, pressed under high pressure, and the edges of the metal case are mechanically united to hold the enclosed assemblage together permanently. The case has 0.2-inch square holes, 1/4-inch centers straight, and is 64-percent open. Of the two fabrics employed, nylon is the stronger, but is inert and has virtually no buffering action. Fiberglas, on the other hand, exhibits a surprisingly high relative degree of buffering action. Neither, however, shows the marked buffering capabilities of plaster-of-Paris, the result being that the effect of large salt content in the soil makes the fabric unit less sensitive to moisture changes and limits the sensitive resistance range of the fabric unit.

For research investigations, it is necessary to correct resistance readings to a constant temperature. Because no thermistor is included with the fabric unit, separate temperature installations are needed.

The special Wheatstone bridge devised for measuring plaster-of-Paris block resistances is also suited to the fabric units.

Bouyoucos (9), working with a nylon electrical resistance unit as described, reported results of laboratory calibrations in 47 soils from the entire U. S. and Canada. These units were calibrated by placing them in a small pan which contains 20 grams of air-dry soil and then covering the units with 20 grams more of the soil. The soil was then saturated until water stood on the surface. The units were worked down into the soil with a small strip of metal and were tapped to remove air bubbles. They were then dried for certain periods of time under normal laboratory conditions, and moisture values were obtained as desired by weighing the entire sample, unit, and pan on a Toledo balance. The calibrations revealed the following resistance relationships for most soils: saturation 150 ohms; field capacity, 2,500 ohms; wilting percentage, 300,000 ohms; and air-dry, 1,000,000 ohms.

A combined fiberglas-plaster block unit has been described by Youker and Dreibelbis (35) for measuring soil moisture under field conditions from saturation to the wilting point. The design combines the advantages of the plaster-of-Paris block with that of the fabric principle. The plaster-of-Paris block serves as a good buffer and contact with the soil, and the fiberglas serves to furnish reliable data in the wet range which the plaster-of-Paris block does not give.

The authors, in commenting on use of the Colman units, stated that the units gave good results most of the time, but following prolonged dry periods they did not respond to increases in soil moisture. Presumably an imperfect contact with the soil at these times caused this.

In 1939, Fletcher (16) made use of the well known fact that water has a high dielectric constant and soil a low one in adapting a resonance method of determining the dielectric constant to the determination of soil moisture. The system was hooked up so that the sum of the capacities of a condenser (C) and a special one to be buried in the soil (Cs) is constant. By reading (C), therefore, the capacity of (Cs) is known. This method is only slightly affected by soil temperature and salt concentration. It has never proven to be entirely satisfactory in the field, however. Anderson (5) placed a specially designed probe-condenser in direct contact with the soil and determined the electrical capacitance with an A. C. Wheatstone bridge excited by a frequency of 1,000 cycles. The data, collected on five Yolo soils covering a range in texture extending from a moisture equivalent of 6.7 to 29.1, indicate that the shape of

the curve giving the dependence of electrical capacitance on soil moisture content, above the permanent wilting percentage over the range of readily available moisture to plants, does not depend appreciably on soil texture.

Anderson and Edlefsen (4) carried out laboratory and field investigations on the use of the electrical capacity of the 2-electrode plaster-of-Paris block as an indicator of soil moisture content. With decrease of soil moisture content, the capacity begins to drop from a rather high value (about 0.070 microfarad) at about the moisture equivalent, finally approaching a relatively constant value (around 0.0003 microfarad) at a little above the permanent wilting percentage of the soil. The authors finally conclude that the method will serve as a practical indicator of the soil moisture content in a body of soil where the blocks can be buried and where the changes in soil moisture content are caused by the removal of the moisture by the roots of actively transpiring plants.

Wallihan (33), attempting to compare the various types of equipment and answer some of the questions involved in using the dielectric method of measuring soil moisture, concludes that condensers having insulated plates have certain advantages over bare electrodes. Concentric arrangements of the condenser plates and proper shielding of the capacity bridge are important conditions also.

In two other important papers published in 1939, Shaw and Baver (30,31) describe a method for measuring moisture changes of the soil *in situ* which utilizes the thermal conducting properties of soil. The apparatus consists of a modified Wheatstone bridge arrangement in which one of the arms consists of a coil of No. 40 enameled copper wire wound on 6 mm. glass tubing. This arm is buried in the soil. A microammeter records detector current and a 6-volt battery is the current source. The bridge is balanced out so that temperature changes in the soil arm affected by a current of 0.1 ampere or more throw the bridge out of balance, thus allowing a current to flow through the microammeter. This is due to the fact that heat is being developed in the soil arm faster than it can be conducted away by the soil; as a result, the temperature of the soil arm rises. Its temperature continues to rise until it reaches a point at which heat is lost as fast as it is gained. The current through the microammeter increases with the temperature of the soil arm. The magnitude of the current at equilibrium reflects the increase in the temperature of the soil arm. It can be seen that the heat conductivity of the soil is the factor that controls the temperature rise. If the conductivity is low, the temperature rise will be large, and if the conductivity is high, the temperature rise will be small. Since the heat conductivity of a soil increases with its moisture content, the size of the current through the microammeter is an index of the amount of moisture in the soil. In studying soil moisture changes in the laboratory, soil was placed in a cylindrical woven-wire

container lined with linen, the soil arm of the bridge was inserted vertically into the soil column, the entire column was saturated overnight, and readings were taken after suitable periods of drainage and evaporation. Since weights of container and dry soil were known, soil moisture could be computed at the time of readings for calibration of the soil arm. Duplication of results in succeeding drying cycles was excellent. The studies show that the readings are not influenced by external temperature conditions or by changes in the salt concentration of the soil solution. For field use it is difficult to obtain good contact between the soil arm and the surrounding soil, and hence its use in the field has not been entirely satisfactory.

The heat conductivity circuit just described was the second one used by Shaw and Baver. In the first one, two soil arms were used, one being inserted in oven-dry soil and the other in soil identical in all respects but moisture content. In this case unbalance in the bridge is the result of the difference in radiation from two identical heater elements, and a variable resistor in the bridge registers the amount of unbalance, instead of having a microammeter to record differences in detector current.

Three years after the work of Shaw and Baver, Johnston (19) introduced the same principle to thermal units that Bouyoucos and Mick had perfected for electrical resistance units. Plaster-of-Paris was cast as a concentric jacket 1/8-inch thick about the 15 mm. glass tubes upon which the heater wires had been wrapped. The function of the jacket was to absorb the heat emanating from the heater coil, making the resulting readings a function of the moisture content of the jacket and eliminating the contact difficulties between soil and elements that arise when non-jacketed heaters are used. These heater elements were placed in two soils of markedly different types to determine whether comparable readings could be obtained at field capacity and again at the permanent wilting percentage in each soil. The tests were made in pots of soil in the laboratory, and results showed comparable readings in the different soils.

LABORATORY CALIBRATION OF UNITS

Kelley (21) described a method for the laboratory calibration of various instruments used in measuring soil moisture *in situ* that is quite similar to the one used by Shaw and Baver. The unit being calibrated is surrounded with 1/2 inch of soil contained in a wire basket lined with cloth. The soil is wet by capillarity and placed in a humidity chamber to drain. It is then removed and subjected alternately to 5 hours' evaporation under laboratory conditions and 19 hours in a humidity chamber. This procedure is continued until the soil no longer loses moisture when exposed to the air. The weights are recorded, and readings for the various instruments are taken each time the soil is removed from the humidity chamber.

A method which parallels Kelley's method very closely is to collect an undisturbed volume sample of a soil and then insert the unit to be calibrated into this core, thus simulating natural conditions more closely. Alternate periods of drying and resting in a moist chamber can then be followed exactly as Kelley described.

TENSIOMETRIC METHODS

A porous cup filled with water and connected to a suitable gage may be used for measuring the tension with which water is held by soil, or pressure in soil water. This negative pressure is often given the name tension or capillary tension. Richards and Gardner (25) describe such an instrument and call it a tensiometer. The pressure in soil water may be either greater or less than atmospheric pressure, which is ordinarily taken as the pressure reference. At points below a water table the pressure is positive, but in unsaturated soil the water in a porous cup must be under negative or vacuum pressure in order to be in equilibrium with the water in the soil. Three types of tensiometers are described and their operation discussed by the authors. They are the indicating tensiometer, which employs a mercury manometer or Bourdon gage for recording capillary tension; the record ing tensiometer for providing a continuous record of tension; and the differential tensiometer, which has two porous cups filled with water and connected to the two sides of a mercury manometer. This latter type provides a convenient means for indicating which way water is moving in a soil.

The range of capillary tension for which tensiometers can be used does not exceed one atmosphere, or the tension required to support a column of water 980 cm. in height. This fact limits the use of tensiometers, since many soils have lost less than one-half of their available water at this tension.

Richards and Neal (26) reported on field tests with tensiometers in which 83 indicating tensiometers and two duplex recording tensiometers were used near Clarinda, Iowa, in the summer of 1936. The study was restricted to fallow plots where the moisture conditions remained well within the operating range of the instruments. The comparatively rapid tension changes which were found indicate that moisture was present in the soil in a connected liquid phase up to within a few inches of the surface. The duplex recording tensiometers installed in fallow soil at 6 and 12-inch depths showed that between these depths the average water moving field (the net force per unit mass of liquid in the soil) was upward except for short periods after rain, and values as high as 16.5 times gravity were recorded in the upward direction.

In 1937, Neal, Richards, and Russell (24) did some work concerning the relationship between capillary tension and moisture percentage for samples of undisturbed Marshall silt loam taken from depths of 0-6 inches,

10-16 inches, 20-26 inches, and 30-36 inches. Four sets of determinations, all on a drying-out curve, are reported. There is a slight variation in the tension exhibited under these conditions for a given moisture content at the four depths in the profile. Richards (27) published in 1942 concerning the newest improvements in design and materials for tensiometer construction, and he describes design and construction of three units in detail.

The importance of associating moisture changes in soils with changes in the energy levels of the soil moisture was further recognized by Haise and Kelley (18) in a paper which had as its purpose to show the relation of heat transfer and electrical resistance in plaster-of-Paris blocks to the tension of the water in the blocks. The possibilities of using these instrument methods as a means of measuring soil moisture tension over the entire range of moisture available to plants was recognized. By means of thermal units cast into Bouyoucos blocks, a pressure membrane extraction apparatus was employed to obtain tension on the units ranging from 1 to 15 atmospheres. Fifteen atmospheres of tension correspond to the tension of soil water at permanent wilting percentage for most soils. Spark plugs mounted in the sides of the pressure chamber provided insulated connections to the units. Before installation in the chamber, the plaster units were immersed in distilled water and left for several hours in an evacuated container. The leads from the units were soldered to the spark-plug terminals. The units were bonded to the membrane by brushing fresh plaster-of-Paris in the desired position on the membrane and then placing the units in the fresh plaster-of-Paris before it had set. The results of this study indicate the following:

(1) The desorption curve on plaster-of-Paris indicates that most of the water is held at tensions below 4 atmospheres, although there is an appreciable loss over the entire range above 4 atmospheres which could not be detected by removal of water from the units.

(2) Bouyoucos blocks continued to register change in resistance above 4 atmospheres of tension with very slight changes in the moisture content of the block.

(3) The thermal units responded to changes in moisture content only so long as an appreciable loss of moisture took place. Inability of these specific thermal units to respond to tensions above 4 atmospheres does not necessarily place any limitations on this method for measuring soil moisture. Porous media having a proper pore-size distribution would undoubtedly produce more satisfactory results.

COMPARISON OF METHODS

Kelley, et al. (20) investigated methods of measuring soil moisture under field conditions and presented their opinions based on the use of 13 gravimetric sorption blocks, 300 tensiometers, 900 Bouyoucos blocks, and 150 thermal units. The outline of soil moisture measuring methods presented earlier in this review is from this paper. An examination of the data from this study reveal the following facts:

(1) Tensiometers function between 0 and 850 cm. (0.85 atmospheres) of water tension, and are the most accurate and practical method in this range. Maintenance is simple and readings are readily obtained.

(2) Bouyoucos blocks function between 1 and 15 atmospheres of tension. Temperatures, salt concentration, physical nature of the block, and variations due to external flow of current between electrodes all cause variation in resistance of the blocks. In humid temperate regions, none of these are considered serious sources of error. This method is the most practical for measuring moisture changes above 1 atmosphere of tension in soils not containing large amounts of salts.

(3) Thermal units function from slightly less than 1 to 4 atmospheres of tension. Soil temperature can be obtained when moisture readings are made, and salt concentration does not affect the readings. In theory the method appears superior to either tensiometers or Bouyoucos blocks. Improvement in design of the porous media are needed to increase the range of effectiveness.

(4) Calibration of gravimetric sorption blocks versus moisture tension in the laboratory was not possible. The data suggest a lag of considerable magnitude in approaching equilibrium.

(5) Difference in soil moisture obtained from replicate plots of the same moisture treatment may be due to one or a combination of the following:

(a) Lack of uniform penetration of the soil by roots
(b) Soil heterogeniety
(c) Uneven growth of plants
(d) Inequalities in the soil surface

Cummings and Chandler (12) made field comparisons of the electrothermal and plaster-of-Paris block methods with the tensiometer method. Plaster-of-Paris block data were unreliable below a tension of 100 cm., and tensiometer data were unsatisfactory above a tension of 930 cm. Data from electrothermal units were not very consistent because of poor contact with the soil.

Soil moisture measurements which depend on resistance of the soil to deforming forces have been attempted, but these cannot be used for continuous in situ measurement. Allyn and Work (1) devised an instrument which they called an availameter. Observations show that the higher the moisture content of soil, the more plastic and less stable it becomes when subjected to a deforming force. The force necessary to cause a given deformation in soil of a given compaction increases as the moisture content decreases. Stability of soil cores was determined by loading a plunger or needle footing of definite diameter until a predetermined penetration into the soil was obtained. Stability and moisture content correlated in a promising way. The device requires an undisturbed soil core from a soil tube approximately 3/4 inch in diameter, and is therefore confined to medium to heavy soil types which give cohesive cores at all moisture contents. Allyn (2) invented a new device known as the stabilimeter for quick field determination of soil moisture conditions. The apparatus consists of a diamond-shaped blade point mounted on a shaft by means of which the blade point can be driven to the desired soil depths. The measurement of the resistance of the soil to the rotation of this point is termed "the soil stability," and is evaluated in terms of torque in inch-pound units. This device was used only in heavy soils in this experiment, and correlated with soil moisture content usually within 0.5 percent. These methods have all of the disadvantages of the gravimetric method, except that there is no delay in obtaining results.

NEUTRON SCATTERING

A method for measuring soil moisture based on the scattering and loss of energy of neutrons when they collide with hydrogen atoms is described by Belcher, Cuykendall, and Sack (6). The precision of this method is claimed to be plus or minus 1 percent. The principal advantages are: (1) different soils seem to have the same calibration curve, (2) inhomogenieties such as rocks do not introduce serious disturbances, and (3) salts or organic matter in quantities encountered under normal conditions do not affect the calibration curve.

A stainless steel or aluminum pipe with a pointed solid end is driven or inserted in an auger hole to the desired sampling depth. The neutron source and Geiger counter are lowered into the pipe to a given depth and left for 5 minutes to achieve radioactive equilibrium. Then a count is made of

returning slow neutrons with an electric scaler. This measurement is usually repeated 2 or 3 times to insure accuracy. The probe containing the neutron source and Geiger counter is then withdrawn and 5 minutes is allowed for decay of radioactivity before a measurement is made at a different depth. To eliminate effects of background radioactivity and instability of the counter and scaler, a measurement is made in a comparison standard at frequent intervals (three or four times each day, or once at each site, or perhaps at every fifth determination depending on the situation). The comparison standard may be a bucket of water, paraffin or other material high in hydrogen. The calibration curve consists of a plotting of the ratio between counts in the soil and the comparison standard.

The moisture determination is for a volume of soil rather than for a given point in the profile. Moisture is measured in an oblate spheroid with a horizontal axis of 12-24 inches and a vertical axis of 12-18 inches. The smaller values are for high moisture contents, and the volume of soil in which moisture is measured varies considerably with moisture content. The comparatively large soil volume sampled has its advantages as well as disadvantages. The advantages are: (1) Moisture values represent an average for a considerable volume and are probably little affected by minor inhomogenieties. Thus, fewer replications are needed to characterize a site. (2) The volume of soil disturbed by the placement of the tube is small in relation to the volume sampled, and the disturbance has no measurable effect. (3) Field calibration checking may be more accurate. For example, the average moisture from three soil tube samples may better represent the area sampled by neutron scattering than the much smaller area of soil in contact with a fiberglas electrode.

The disadvantages of sampling the large volume of soil are: (1) It is not simple to measure moisture in soil horizons thinner than the 12-18 inch vertical layer sampled. (2) It is difficult to determine exact location of a wetting front. (3) Somewhere above a depth of 6-9 inches from the surface, neutrons escape from the soil so that the universal calibration does not hold for shallow depths of sampling.

This method of soil moisture measurement has considerable promise, and methods and equipment are being improved to give more precision and simplify procedures.

USE OF SOIL MOISTURE DATA

Soil moisture as determined by the gravimetric method, either directly or to calibrate an indirect method, does, as previously mentioned, produce results expressed as percent of oven-dry weight. Such results can then be converted to percent of soil volume (Pv) if the bulk density of the soil is

known. The expression of soil water on a volume basis is more useful to all investigators because it measures the actual quantity of water in the soil in relation to the total soil volume. Bulk density of soils can be determined by collecting undisturbed samples of a known volume from the sampling depths desired, and obtaining their oven-dry weight. Both soil volume and weight should be based on soil which passes a 2-mm. sieve. When sufficient samples have been taken, the average rock content for different horizons can be used to express actual average bulk density for the soil.

Under certain conditions percent by weight (Pw) is an adequate expression of soil moisture. If comparisons of moisture contents between two or more areas on similar soils are desired, Pw is then sufficient. However, if bulk densities are variable, soil moisture content should be expressed as Pv or inches of water.

As noted previously, plant scientists are interested primarily in the amount of soil water available to plants. In order to determine available water, the permanent wilting point of the soil must be known. The permanent wilting point marks the lower limit of available water for plants. Veihmeyer and Hendrickson (32) discuss several methods of determining the permanent wilting point and compare their relative advantages and disadvantages. Since this is an exhaustive subject in itself, no attempt will be made to present this material in this paper. Richards and Weaver (29) introduce a new method employing a pressure chamber. A gas pressure is applied to small saturated soil samples in order to simulate the force which plants exert to withdraw soil moisture to the wilting point.

In many soil moisture investigations, the relation of soil moisture content to the field capacity and saturation is needed. The field capacity is also defined and its determination adequately discussed by Veihmeyer and Hendrickson (32). This important constant is ordinarily the upper limit of availability of water to plants and also represents the maximum amount of water which a soil can hold against the forces of gravity.

The saturation constant can be determined as follows: Collect undisturbed volume samples in a core type sampler, saturate them about 16 hours in an open tank, and weigh fully saturated. Next, dry the samples to constant weight and compute the moisture content at saturation. Bulk density can be obtained from these same soil cores.

The determination of soil moisture for any purpose has greater meaning when these soil moisture constants are known. Nevertheless, when only comparisons of relative moisture levels or knowledge of trends are desired, a simple expression of total soil moisture content is adequate for the purpose.

GENERAL DISCUSSION

Lack of knowledge in the field of soil moisture can be attributed to a lack of adequate means of measurement rather than to a lack of interest on the part of investigators. It can be seem from the review of methods used that the ideal conditions for making soil moisture studies exist when nondestructive testing can be used, when moisture in the soil itself can be measured, and when the soil is undisturbed and free from unnatural influences. It is also a requirement that continuous records be obtainable in the range of soil moisture from air-dryness to saturation.

Of the methods available for use at this time, those employing fabric electrical resistance units most nearly approach the ideal. The use of radioactive materials, when further developed, will almost exactly match the ideal. Tensiometers are excellent devices for measurement in the wet range, and, used in conjunction with fabric units, provide records for the complete range of soil moisture.

One serious difficulty with all continuous measuring instruments, however, is that calibration in the field against gravimetric samples is not precise because of soil heterogeniety, uneven plant growth and root penetration, and uneven soil surface conditions. In sampling for calibration purposes, a certain portion of each experimental site is destroyed for further sampling.

As research continues, methodology of continuous soil moisture measurement in the field may be eliminated as a limiting factor, and then investigators can devote their energies exclusively to studies of the most dynamic of all soil characteristics--the soil water complex.

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